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Observation of Parallel Viscosity in the CHS Heliotron/Torsatron

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Observation of Parallel Viscosity in the CHS Heliotron/Torsatron

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Abstract

Damping of the toroidal velocity owing to parallel viscosity is observed in the plasma with a tangential neutral beam injection in the CHS Heliotron/Torsatron device. Toroidal velocity profile is dominated by the perpendicular viscosity when magnetic field modulation is weak near axis. However, the parallel viscosity is found to be dominant when the modulation is strong enough and to increase in proportion to the square of the modulation of magnetic field. The absolute values of the viscosity agree with the neoclassical prediction within a factor of three.

Keywords: Plasma flow, Viscosity, Heliotron/Tosatron

In toroidal plasma, poloidal and toroidal rotation velocities are determined through the balance between the input torque and damping force in steady-state. In tokamak H-mode plasma[1], significant poloidal rotation has been observed[2,3]. In a recent theoretical model, the poloidal rotation is assumed to be driven by the poloidal torque associated with the ion-orbit loss[4] or imposed radial current[5,6] and is damped by the neoclassical parallel viscosity. However, the poloidal viscosity has not been measured precisely enough for a comparison with the neoclassical theory[7,8], because of the difficulty in estimating the poloidal torque. This is because the fraction of the edge ion-orbit loss is sensitive to the electric field produced by the ion-orbit loss itself[9]. On the other hand, toroidal rotation is mainly driven by the torque given by the neutral beam, in plasmas with tangential neutral beam injection. There have been many observation of toroidal rotation in tokamaks[10-13], but the damping is mainly due to an anomalous perpendicular viscosity (radial diffusion of momentum). Because the magnetic field ripple in toroidal direction is so small that the effect of the neoclassical parallel viscosity in toroidal rotation is easily masked by the anomalous perpendicular viscosity. In helical devices, the helical ripple is large enough to affect toroidal rotation. The poloidal rotation have been measured on Heliotron-E[14] and Wenderstein VII-A[15], however, toroidal rotation and discussions on the damping mechanism has not been reported.

Even though the potential importance of parallel viscosity in the H-mode physics, the experimental measurement of it is far from satisfaction[6]. A preliminary report has been made on the measurements of the toroidal and poloidal velocities in the Compact Helical System with tangential neutral beam injection and on the viscosity[16]. In this article, we investigate the toroidal rotation velocity in a wide range of density and magnetic field ripple, and a comparison of the measurements with the neoclassical theory is discussed.

The Compact Helical System (CHS)[17] is a Heliotron/Torsatron device (the poloidal period number l = 2 and toroidal period number m = 8) with the major radius (R) of 1 m, an average minor radius (a) of 20 cm and a rotational transform at the plasma edge ι_a [= $RB_\theta/(aB_\varphi)$, where B_φ, B_θ are the toroidal and poloidal magnetic fields, respectively] of ~ 1. The magnetic field has a helical ripple ($\varepsilon_h^{m,l}$) with a toroidal periodic number of m= 8 and a poloidal periodic number of l= 0,±1,±2,±3, and a toroidal ripple ($\varepsilon_t \sim a\rho/R$, where ρ is the averaged normalized minor radius). Modulation of the magnetic field strength γ is defined as $\gamma^2 = \langle(\partial B/\partial s)^2\rangle/B^2$, where s is the length along the magnetic field line and $\langle\rangle$ is a flux surface average operator. This magnetic field modulation is mainly attributed to a helical ripple and is of the order of $(m\varepsilon_h/2\pi R)$, and can be much larger than that due to the toroidal effect $(\varepsilon_t/2\pi R)$. In CHS, the magnetic field ripple of plasma center can be changed by shifting the magnetic axis so as to produce significant parallel viscosity. The major radius of the vacuum magnetic axis (R_{ax}), which is calculated in the vacuum magnetic field configuration, is scanned from 89.9 to 101.6 cm in our experiments. Central helical ripple $\varepsilon_h^{m,l}(0)$ is negligible when the major radius is set at 90 - 95 cm; however, it increases sharply for R_{ax} > 95 cm and reaches 8% at R_{ax} = 101.6 cm.

Plasma is produced initially by the electron cyclotron heating (ECH) and sustained with tangential NBI (injection energy of 32.5 keV and absorbed power of 0.5 MW in the direction parallel to helical current). The line-averaged density reaches around 2 x 10^{13} cm^{-3} after NBI is injected. Figure 1 shows the change of profiles of toroidal/poloidal rotation velocity, electron/ion temperature, electron density, and modulation of magnetic field strength γ, as a result of the major radius scan, which is controlled by vertical field strength. Profiles of ion temperature and the poloidal/toroidal rotation velocity are measured with charge exchange spectroscopy using a two-dimensional CCD detector[18,19]. Profiles of electron density and temperature are measured with Thomson scattering system. We evaluate γ by averaging $(\partial B/\partial s)^2$ along the field line for one toroidal turn. Structure of the magnetic field is derived from the finite 3-D β equilibrium code VMEC[20], based on the kinetic data in the experiments. As demonstrated on the ion temperature profile, the axis of plasma (R_{ax}) is shifted outward due to finite β effect and this Shafranov shift is 2 - 5 cm depending on the plasma and beam pressure and rotational transform ι [$= RB_\theta/(a\rho B_\varphi)$]. Details of the measurements of Shafranov shift in CHS will be reported elsewhere. The toroidal rotation velocities show a significant damping as the axis of plasma is shifted outward, although the energy confinement time measured with diamagnetic loop increases from 1.5 (R_{ax}=89.9 cm) to 2.5 ms (R_{ax} =97.4). The poloidal rotation velocities also show similar damping behavior in the core region; however, they show no change near the plasma edge ($\rho \sim 0.7$). The global confinement is improved by shifting the plasma outward, but the the particle confinement in the core region decreases as observed in electron density profiles. The noticeable difference of particle transport between for R_{ax} =94.9 cm and for R_{ax} =97.4 cm seems to be associated with the change of toroidal rotation profiles, but the effect of plasma rotation on particle transport[21] is out of the scope of this paper and will be discussed elsewhere. We note that these toroidal rotation damping and density profile flattening are also observed when the direction of magnetic field is reversed.

In the core region of $\rho < 0.5$, the plasma rotates almost parallel to the magnetic field line, as shown in poloidal and toroidal rotation profiles, since rotational transform in this region is 0.3 - 0.5. Several mechanisms can contribute to the damping of the parallel velocity ($V_{//}$), such as transit time magnetic pumping (TTMP) of the rotating ions due to the modulation of B (parallel viscosity term $\mu_{//}V_{//}$), radial diffusion of momentum due to the velocity shear (perpendicular viscosity term $\mu_\perp \nabla v_{//}$) and collision with a neutral particle [charge exchange momentum loss $n_0 <\sigma_{cx} v> v_{//}$, where n_0 is the neutral density and $<\sigma_{cx} v>$ is the charge exchange rate coefficient]. Charge exchange loss becomes dominant only near the plasma edge, and damping due to $\mu_{//} v_{//}$ and $\mu_\perp \nabla v_{//}$ terms becomes important in the region of our interest ($\rho <$ 0.6).

Parallel velocity near plasma center is mainly determined by the perpendicular viscosity for R_{ax} = 89.9 cm, since the modulation of B is too small to affect the plasma rotation near axis. On the other hand, parallel velocity is damped by the parallel viscosity for R_{ax} = 97.4 cm , where the modulation of B is 0.4 m^{-1} at the plasma center as shown in Fig. 2. To compare the measured parallel velocity with the theoretical estimate, the neoclassical (NC) parallel viscosity is taken for the references[22,23]. The NC parallel viscosity is proportional to square of the modulation of B as $\mu_{//}^{NC} \propto \{(\partial B/\partial s)^2/B^2\} F(\nu_i{}^*)$, where $\nu_i{}^*$ is the ion normalized collisionality. As estimated in Ref.23, the parallel viscosity is expressed simply as $\mu_{//}^{NC} = C\{\langle(\partial B/\partial s)^2\rangle/B^2\}(R/m) v_{th}$ in the plateau regime, where C is the numeral coefficient. We examine the fitting of measured parallel velocity with $(\mu_{//}, \mu_\perp)$. The perpendicular viscosity of $\mu_\perp$ = 3.5 m^2/s in addition to the NC parallel viscosity gives the best fit of the measured parallel velocity for R_{ax} = 89.9 cm, the latter mechanism affects plasma rotation only ρ > 0.6. The central rotation velocity may be explained alternatively by increasing the values of $\mu_\perp$ up to 18 m^2/s with $\mu_{//}=0$; however, the radial momentum diffusion alone can not explain the damping of the parallel velocity at $\rho > 0.6$. The estimation by the large perpendicular viscosity alone can not explain the significant change in the velocity between R_{ax}= 89.9 cm and R_{ax}= 97.4 cm either. In the case of R_{ax}= 97.4 cm, the parallel viscosity becomes dominant and the additional perpendicular viscosity changes the estimate of velocity by only 20%. The best fit of the parallel viscosity profile for R_{ax}= 97.4 cm gives $\mu_{//} = 3 \times 10^3\ s^{-1}$ which is smaller than the calculation by Shaing by a factor of three. Perpendicular viscosity to fit the experimental data is comparable to the measured ion thermal diffusivity (~ 5 m^2/s) and larger than that of the neoclassical prediction (~ 2 m^2/s) by a factor of two.

The parameter dependence of the viscosity is studied by changing the plasma density and the field ripple. Toroidal rotation velocity is measured for R_{ax} = 92.1 cm (perpendicular viscosity is dominant) and for R_{ax} = 94.9 cm (parallel viscosity becomes important) in the wide range of electron density from $0.7 \times 10^{13}/cm^3$ to $6 \times 10^{13}/cm^3$. The perpendicular viscosity is found to decrease roughly proportional to $1/n_e$ as the global confinement is improved by increasing the electron density. This density dependence concludes the existence of anomalous radial diffusion of the momentum as observed in tokamak plasma. However, the parallel viscosity does not change for this density scan, confirming plateau neoclassical prediction.

The observation confirms that the parallel viscosity is proportional to the square of the modulation of the magnetic field strength. To demonstrate the γ^2 dependence of parallel viscosity, the effective viscosity μ_{eff}, which is defined as $\mu_{eff}^{-1} = v_{\parallel}\, m_i n_e(0)/f_{NBI}(0)$, where $f_{NBI}(0)R$ is a torque by NBI. As shown in Fig.3, this effective parallel viscosity shows γ^{-2} dependence as predicted by the neoclassical theory in the region where parallel viscosity becomes dominant, $\gamma > 0.2$. When the modulation of B decreases below 0.2, the parallel velocity becomes small and perpendicular viscosity become dominant in turn. Large parallel viscosity and significant charge exchange loss near the plasma edge becomes a boundary condition to determine the central parallel velocity in the radial transport of momentum. One of the main errors in evaluating the modulation of B in the measurements are due to the uncertainty of the description of finite β equilibria.

In conclusion, the parallel viscosity is found to increase in proportion to the square of the modulation of magnetic field and show no dependence on plasma density, the characteristics of which agree well with the neoclassical prediction in plateau regime. Their quantitative agreement are within a factor of three. However, when the magnetic field modulation is weak, the perpendicular viscosity (anomalous radial diffusion of momentum) becomes dominant as in tokamak plasma.

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Figure Captions

Fig.1. Radial profiles of (a) ion temperature, (b) toroidal rotation velocity (c) poloidal rotation velocity (d) modulation of magnetic field strength γ (where $\gamma^2 = \langle(\partial B/\partial s)^2\rangle/B^2$) (e) electron density and (f) electron temperature for R_{ax} of 89.9 cm (closed circles), 94.9 cm (asterisks) 97.4 cm (open circles), where ρ is normalized averaged minor radius. Doted line in (a) stands for a fraction of the helical ripple at the plasma center as a function major radius.

Fig.2. Radial profiles of the parallel velocity with estimates of velocity by the neoclassical parallel viscosity (dashed line) and by radial diffusion of the momentum (chain lines) and by the combination of the parallel viscosity and radial diffusion (solid line) for the major radius of (a) 89.9 cm and (b) 97.4 cm, where $\mu_{//}^{NC}$ is a parallel viscosity in the plateau regime.

Fig.3. Inverted central parallel viscosity derived from the measured central parallel velocity, density and momentum input as a function of the central modulation of magnetic field strength γ. Dashed line is an estimate by the neoclassical parallel viscosity and the solid line shows the radial diffusion of the momentum effect on the measurements.

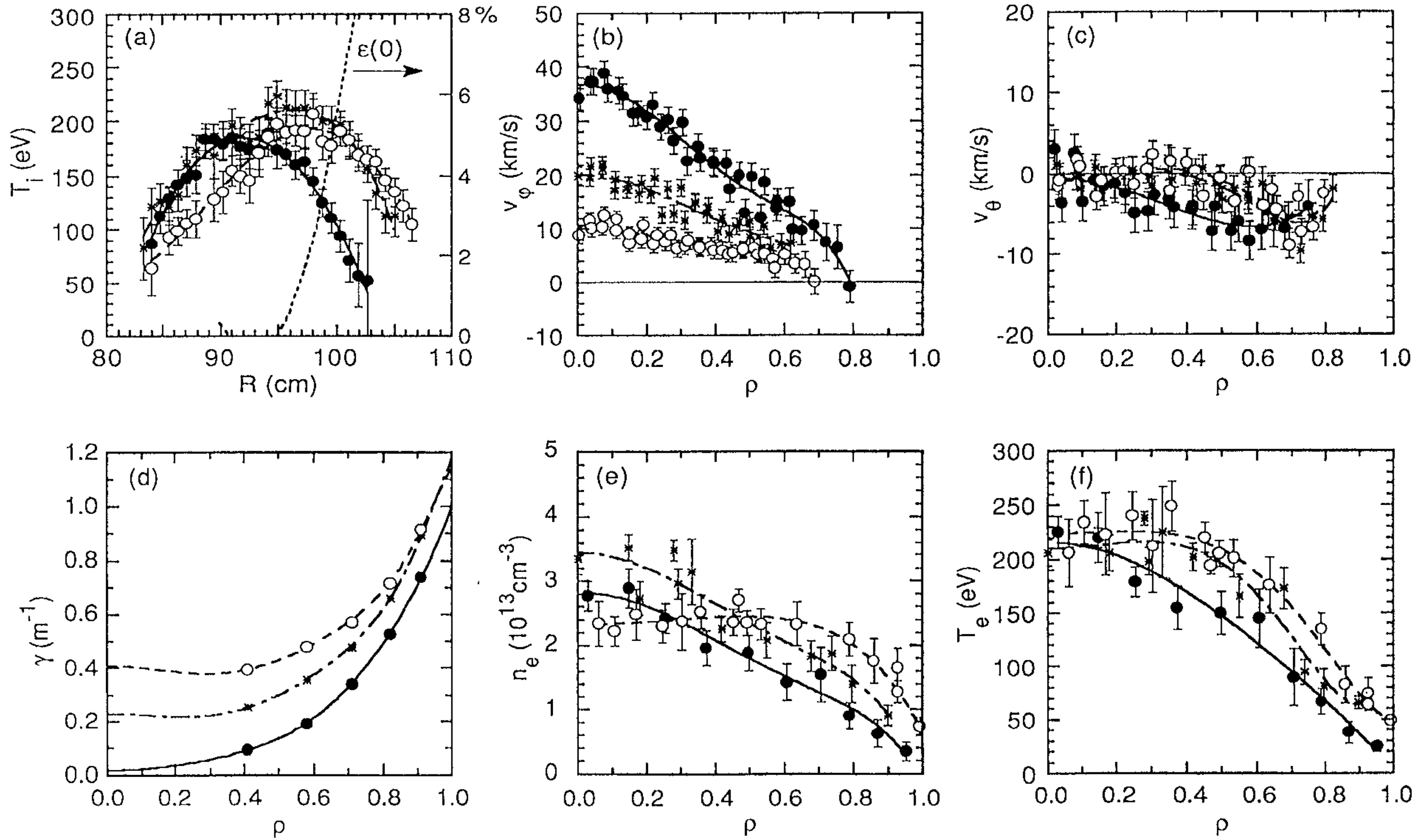

Figure 1

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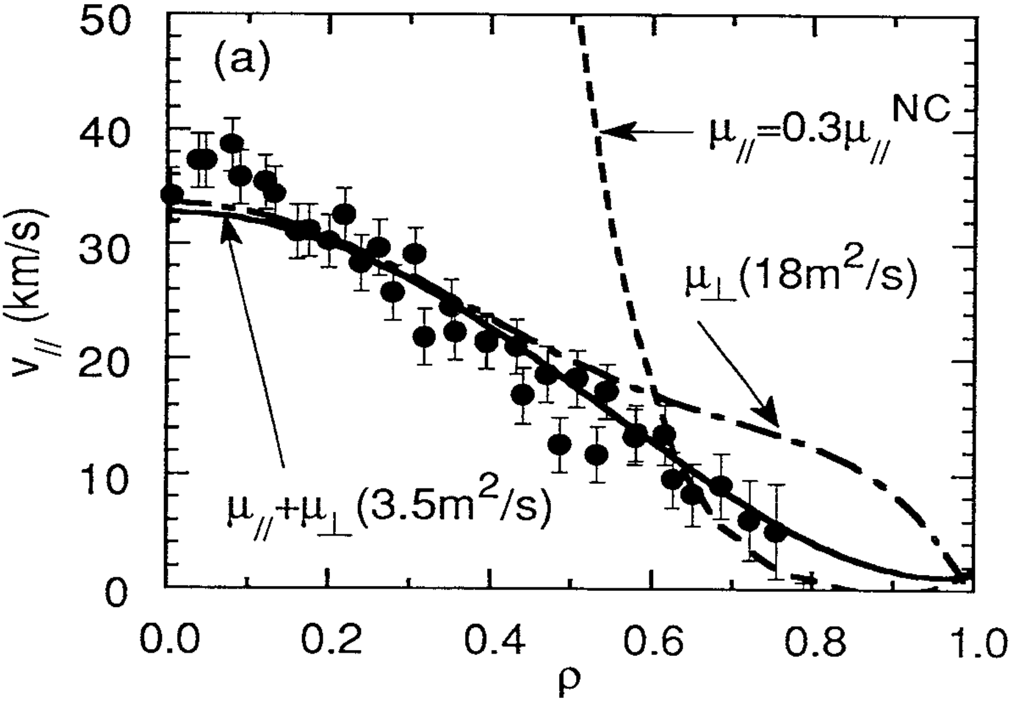

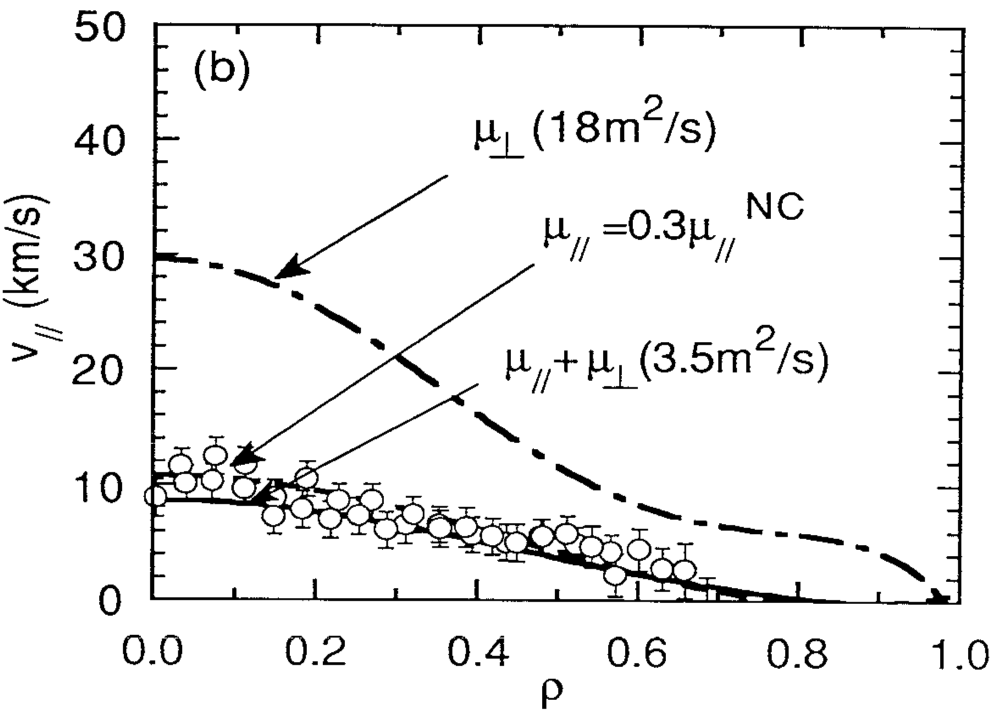

Figure 2

K.Ida et al.

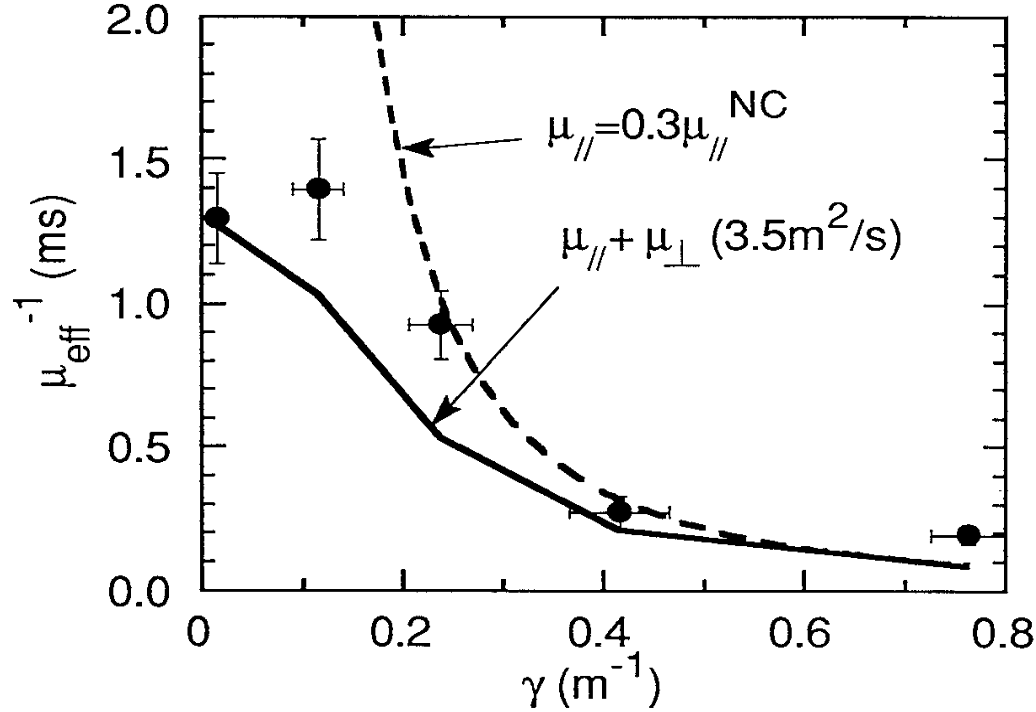

Figure 3

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